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NASA Technical Memorandum 106245
AIAA–93–3263

Enhanced Mixing of a Rectangular Supersonic Jet by Natural and Induced Screech

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Prepared for the
AIAA Shear Flow Conference
sponsored by the American Institute of Aeronautics and Astronautics
Orlando, Florida, July 6–9, 1993

NASA

ENHANCED MIXING OF A RECTANGULAR SUPERSONIC JET BY NATURAL AND INDUCED SCREECH

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Abstract

The influence of shear layer excitation on the mixing of supersonic rectangular jets was studied experimentally. Two methods of excitation were used to control the jet mixing. The first used the natural screech of an underexpanded supersonic jet from a converging nozzle. The level of the screech excitation was controlled by the use of a pair of baffles located to block the acoustic feedback path between the downstream shock structure and the nozzle lip. A screech level variation of over 30 decibels was achieved and the mixing was completely determined by the level of screech attained at the nozzle lip. The second form of self-excitation used the induced screech caused by obstacles or paddles located in the shear layers on either long side of the rectangular jet. With sufficient immersion of the paddles intense jet mixing occurred and large flapping wave motion was observed using a stobed focused Schlieren system. Each paddle was instrumented with a total pressure tap and strain gages to determine the pressure and drag force on the square cross-section paddle. Considerable drag was observed in this initial exploratory study. Future studies using alternate paddle geometries will be conducted to maximize jet mixing with minimum drag.

Introduction

The objective of this research is to study ways in which the mixing of a supersonic rectangular jet can be significantly enhanced using excitation or other shear flow control means which could find practical application in a single or multiple jet mixing or ejector device. It is intended that this excitation device be a natural source which feeds upon the steady flow for its energy rather than requiring an external power source of any kind. Several flow self-excitation devices have been reported in the literature including the "whistler nozzle" by Hill and Greene[1,2] and Hussain and Hasan[3], and the flip-flop nozzle extensively studied by Viets[4] for subsonic flows and more recently by Raman[5] et al. for supersonic jet flows. The natural screech, produced by the underexpanded supersonic jet as discussed and modelled by Powell[6] and Tam[7], was observed by Glass[8] to excite a round jet and enhance the mixing. A study of an underexpanded converging high aspect ratio rectangular nozzle was conducted by Krothapalli[9] et al. in which the pressure ratio and thus the fully expanded Mach number was varied. Maximum jet mixing was observed at the pressure ratio that produced the highest screech level. Lepicovsky[10] et al. reported the reduction of mixing for a round underexpanded supersonic jet by reducing the screech level using cancellation from an upstream baffle. The use of downstream baffles presented here to interrupt the feedback loop between the shock cells and the nozzle lip follows the early work of Hammitt[11], and Davies and Oldfield[12,13]. The use of upstream baffles to reduce the screech level by reflection has been reported by Nagel[14] et al. and Norum[15]. An early photographic study demonstrating the reduction of screech tones by altering the feedback loop using sound absorbing materials was provided by Poldervaart[16] et al. Seiner[17] wrote an excellent review which includes the subject of the screech feedback loop.

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The objective of the first part of the research reported here was to quantify this mixing enhancement due to the natural screech. Rather than varying the Mach number to alter the screech level, the Mach number was held constant while the feedback loop was systematically altered to produce the extremes in the screech level. This was accomplished by locating a baffle downstream from the jet exit at a position which minimized the screech level but did not intrude into the jet flow. A reduction of about 30 decibels was observed in the screech level back at the nozzle lip and the jet mixing drastically decreased with a doubling of the jet potential core observed. Baffles were also tried in the reflecting mode upstream of the nozzle lip. This upstream position did not provide as large a reduction in the screech level compared to placing the baffles between the shock structure and the nozzle lip. When the two baffle sections were spread to the maximum and the baffle parked back at the nozzle exit location, an increase in screech level and jet mixing over that of the unbaffled natural jet were observed similar to the observation of Glass[8]. It appears that the initial mixing of this rectangular underexpanded supersonic jet is completely dominated by the screech feedback process which provides a high level of excitation back at the nozzle lip. When at its high screech level, the natural jet was observed to have a fairly high level flapping mode instability as observed with a swept strobed focused Schlieren system.

The second part of this research effort involves the enhancement of jet mixing using induced screech. The mixing is greater than that of the jet with natural screech excitation, and the phenomena is more controllable and consistent. The induced screech discussed here is a modification of what has been termed edge-tone instability. Edge-tones have been studied extensively with excellent early modelling of all of the elements of the process reported by Powell[18] and a fairly recent review being reported by Blake and Powell[19]. Rockwell and his associates have performed extensive studies and flow visualizations of the details of the flow as it impinges on the downstream wedge or edge. He has a broad review of these and other contributions in reference 20. More recently, Lucas and Rockwell[21] have extended the edge-tone studies to include nozzle asymmetry. In a very recent paper, Crighton[22] provides a linearized model for an idealized jet impinging upon a flat plate.

In the above references most of the attention has been paid to the physics of the individual phenomena involved in the edge-tone generation but little attention has focused on the mixing enhancement of the jet which might occur due to the excitation of the jet. Krothapalli[23] et al. have reported the mixing enhancement observed in a multiple jet arrangement when a wedge is inserted into the middle of one of the jet flows 6.33 nozzle widths downstream from the nozzle lip. All of the five subsonic jets (M=0.87) responded with increased mixing. This very interesting observation did not seem to be pursued. Krothapalli and Horne[24] followed the earlier work with a more detailed study and flow visualization of the flow impinging upon the downstream wedge but mixing enhancement using edge-tone exciters seems to have been dropped. This may be due to the obvious large drag penalties which would occur with a wedge inserted into the center of a high speed jet. In the study reported here, this drag penalty is minimized by locating the obstacles, in this case small square rods referred to as paddles, on each side of the rectangular jet outside of the main jet flow. The paddles are moved into the jet shear layer just far enough to obtain the desired mixing enhancement. Of course, as the paddles are immersed further into the jet shear layer, increases occur in the oscillating pressure source on the paddles, in the induced screech level back at the nozzle lip, in the amplitude of the flapping mode instability, in the jet mixing, and in the paddle drag.

The significant mixing increase due to the paddles and the induced screech is obvious from the data shown in this paper. The extension to multiple jets either open or in a shroud should be no problem. The main question is whether the losses incurred to obtain the desired mixing can be accommodated. In an attempt to answer this question total pressure taps were located on the paddles and strain gages were mounted on the paddle support arms to quantify these losses. A future study will include paddles of different cross-section to determine if lower loss profiles can provide the tone generation to sustain the mixing enhancement.

Experiment

Air Flow Facility

A schematic drawing of the flow facility used in this experiment is shown in Fig. 1. The high pressure air enters at the left into the 76 cm diameter plenum where it is laterally distributed by a perforated plate and a screen. Two circumferential acoustically treated splitter rings remove the upstream valve and entrance noise. The flow is further conditioned by two screens before undergoing two area contractions of 3.5 and 135 for the rectangular nozzles used in this experiment.

A photograph of the flow facility is shown in Fig. 2. The 76 cm plenum is prominent in the middle of the picture. The optical beam supporting the swept strobed focused Schlieren system is seen below the nozzle. A small amount of acoustic treatment wrapping is shown around the optical beam. During actual data acquisition, considerable additional acoustic treatment is used on the beam, on the plenum face, around the nozzle shank, and on the small support beams holding the two paddles.

Nozzle and Paddles

A close-up view of the nozzle is shown in Fig. 3. A 6.4 mm microphone is seen taped to the nozzle just behind the nozzle lip. A set of full length paddles (76 mm) are mounted in their support structure. This

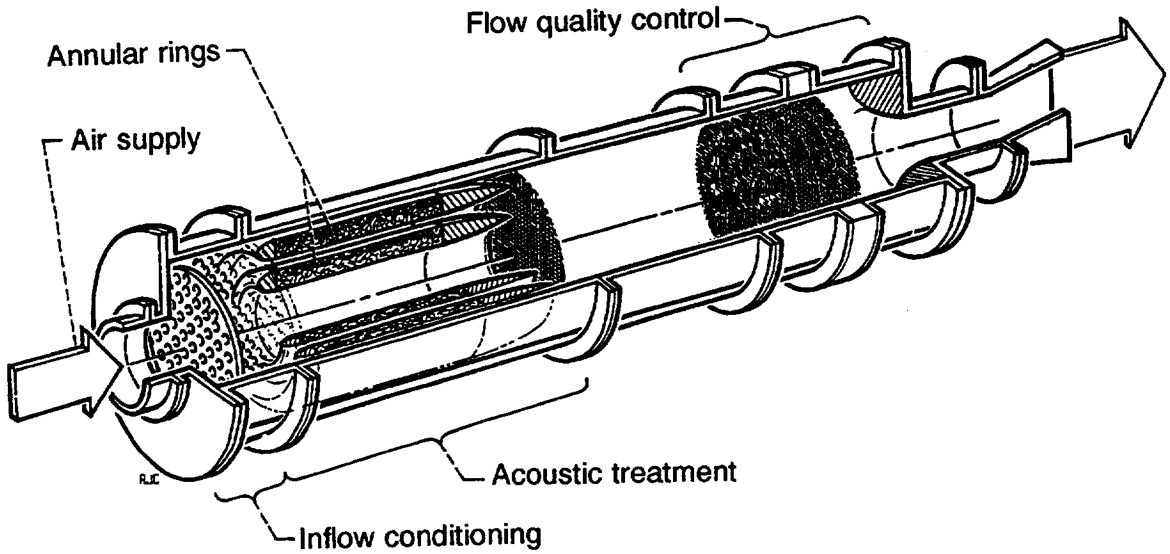


Fig. 1. Schematic of supersonic jet flow facility

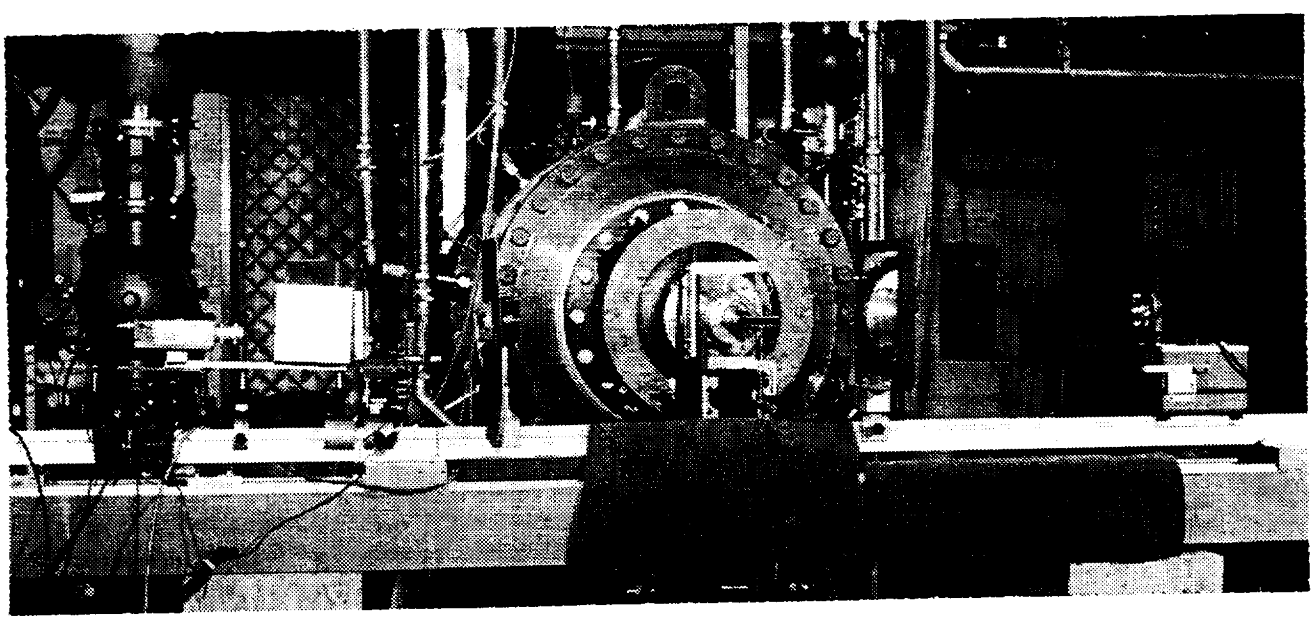


Fig. 2. Jet flow facility and Schlieren optical system

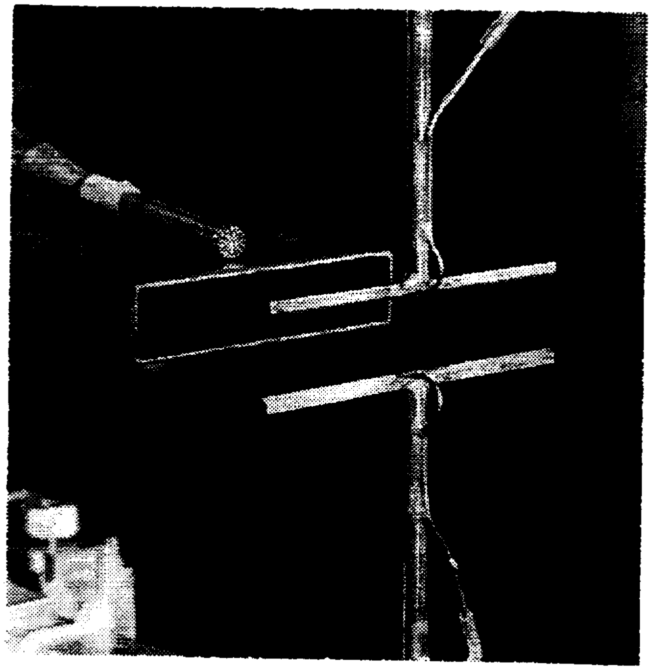


Fig. 3. Nozzle and Paddles

structure has three-dimensional movement and paddle spacing adjustment which are remotely controlled from the control room. On the paddle support shafts the tubing for the total pressure taps can be seen. These pressure taps face toward the nozzle and are flush with the flow side of the paddle. The strain gages and wires are also mounted on these support shafts. These measure the axial force on the paddle. The horizontal placement of the nozzle and paddles shown in Fig. 3 is used only for the Schlieren flow visualization experiments. During aerodynamic and acoustic test runs, the nozzle and paddles are positioned vertically and a simpler, more sturdy paddle support system is used.

In addition to the 76 mm long paddles shown in Fig. 3, shorter paddles of 38 mm and 13 mm length were tested although the data are not presented in this paper. Two rectangular nozzles were used in these experiments. The converging nozzle, nozzle 4, has exit dimensions of 13.2 and 65.8 mm with an aspect ratio of 4.97. The converging-diverging nozzle, nozzle 6, has exit dimensions of 14.1 and 68.1 mm for an aspect ratio of 4.82, and it has a throat dimension of 12.5 mm.

Swept Focused Strobed Schlieren System

The focused Schlieren system seen in Fig. 2 was designed resembling that of Weinstein[25]. The strobe light control system was designed and built in-house to accommodate the needs of this experiment. The control system functioned in the following manner.

1. The vertical sync pulse from the video camera was sensed.
2. A phase delay was then started at the first zero crossing of the screech tone which was measured by the microphone mounted on the nozzle.
3. After a prescribed phase delay, the strobe was fired.

Up to this point the electronics are quite ordinary. With a fixed phase delay the motion of the flapping jet could be stopped for viewing. The interesting addition here is that the phase delay could also be continuously swept through one cycle of the screech and the video displays the flapping motion of the jet instability. The stobed Schlieren system was modeled after that described by Wlezien and Kibens[26].

Aerodynamic Instrumentation

Since the exiting flow of the nozzles in this experiment was supersonic, considerable measurement problems would have been encountered in using hot wire or hot film anemometry. These difficulties were avoided by just measuring the total pressure referenced to room pressure using a simple total pressure tube of 0.8 mm outside diameter. Results are presented derived from this raw total pressure, often called P_{T2}, which would be the total pressure downstream from the bow-shock which stands ahead of the total pressure tube in supersonic flow. In the subsonic flow regions this data was adequate, but for the supersonic flow regions it was recognized that the data should be used qualitatively for comparison purposes only.

The data for most of the axial traverses of the jet also included static pressure as measured by a 1 mm outside diameter dual cone probe based on the design of Pinckney[27]. However, a calibration of the probe in supersonic flow indicated uncertainty concerning the actual axial location at which the static pressure was being measured. Thus it was felt that it was safer to present the results based upon raw total pressure which is sufficient to present the phenomena of interest here.

Experimental Procedure

Two separate experiments are actually reported in this paper. The first involves the study of natural screech in the jet mixing process of an underexpanded supersonic jet from a converging rectangular nozzle. A set of baffles (each being 25.4 cm by 17.5 cm with the larger dimension parallel to the larger nozzle dimension) were mounted downstream of the nozzle in a manner similar to that of the paddles as shown in Fig. 3. The spread and three dimensional position of the baffles were remotely controlled. The maximum spread of the baffles was used to obtain the desired results while providing minimum interference to the jet shear layer. Of course, some obstruction to the low velocity entrained flow was unavoidable. For one part of the experiment, the baffle spread and position was varied to provide maximum reduction of the acoustic feedback path from the shock structure to the nozzle lip. A considerable gap between the jet shear layer and the baffles could be allowed at the higher Mach numbers since the acoustic waves trying to follow this path were refracted into the jet by the strong velocity gradient of the shear layer. For the lower supersonic Mach numbers it was harder to obtain nearly complete feedback path blockage. The results of each baffle position were monitored by observing the screech pressure magnitude at the nozzle lip as measured by the 6.4 mm microphone mounted on the nozzle as seen in Fig. 3. Minimization of the screech tone using cancellation of the acoustic field near the nozzle lip due to reflection from an upstream baffle was also attempted. This method, similar to that of references 14 and 15, did not produce as large a screech reduction as the downstream baffles and was thus abandoned. A second position of the baffles for this experiment was to mount them even with the nozzle lip. The baffles were spread to the maximum to provide the least interference with the entrained flow. The screech tone pressure at the nozzle lip was observed to be large for this baffle position apparently due to acoustic reflection and amplification as previously observed by Glass[8]. No effort was made to maximize the screech amplitude in this phase of the experiment. A third element of this phase of the experiment was to measure the screech tone and jet total pressure axial dependence without any baffles.

The second experiment involved induced screech (or edge-tones) using obstacles (here called paddles) in the outer portion of the shear layer of the jet as pictured in Fig. 3. A converging- diverging rectangular nozzle was used for this experiment and was operated at design Mach number to minimize the natural screech which may have interfered with the induced screech when the latter was at low levels. The position of the paddles in the shear layer was monitored by observing the total pressure at the paddle tap facing upstream on the flow-side edge of the paddle. The paddles were moved axially in the shear layer (while maintaining constant paddle total pressure) and the response of the jet was observed. The jet responses monitored were the induced screech pressure levels and narrow band frequencies at the nozzle lip and the jet centerline total pressure at $X/H_{exit} = 12.6$, which was an indicator of jet mixing. The usual saw-tooth variation of frequency dependence with paddle position was observed centering around a Strouhal frequency of 0.19 (based on nozzle small dimension H_{exit} and jet exit velocity). Three axial positions of the paddles produced large jet response and more detailed aerodynamic and near-field acoustic data were taken for these positions although only data for the most downstream paddle position will be presented in this paper.

Results

The results of the two experiments will now be presented. First the effects of natural screech on the mixing of the jets from a converging and a converging-diverging rectangular nozzle will be explored. The extremely powerful induced screech effect will then be shown for a converging-diverging rectangular nozzle operated at design Mach number. For each of the two experiments, flow visualizations obtained with the stobed Schlieren system will be shown first to provide a picture of the flow phenomenon to be discussed. These will then be followed by quantitative data to illustrate the magnitude of the jet mixing alteration. The procedures involved in the data acquisition have been adequately discussed in previous sections and will not be repeated here. In the following discussion, a reduction in measured total pressure (except where caused by shocks) is interpreted as a reduction in available energy of the jet due to mixing with the ambient flow.

Natural Screech and Jet Mixing

A Schlieren photograph of one frame of a video sequence is shown in Fig. 4. The nozzle is converging nozzle 4, operated underexpanded (over pressured) at a pressure ratio which would provide a fully expanded Mach number (M_{exp}) of 1.30. Recall that the view is that of the small nozzle dimension with the large dimension being perpendicular to the plane of the photograph. The jet is exposed to high level screech self-excitation and is seen to exhibit high amplitude flapping oscillations. The flapping mode instability appears to grow rapidly at about three jet exit small dimensions (H_{exit}). The shock structure is seen even in the flapping part of the jet and streaks of fluid seem to ripped off from the crests of the waves.

A Schlieren photograph similar to that of Fig. 4 is shown in Fig. 5 except that the fully expanded Mach number $M_{exp} = 1.4$. It is at this Mach number that a full sequence of flow visualizations is available. Note that comparing Figs. 4 and 5 shows the higher Mach number

Fig. 4. Jet flapping mode due to screech excitation natural jet, nozzle 4, $M_{exp}=1.30$

Fig. 6. Jet flapping mode amplitude increase with baffles located at nozzle 4 exit plane, $M_{exp}=1.4$

jet to expand slightly more, have longer shock spacing, and appear to have the flapping oscillation start rapid growth further downstream. In Fig. 6 the set of baffles discussed earlier are mounted in the plane of the nozzle 4 exit and are seen to obstruct the view of the nozzle although there is a large space for the flow to exit the nozzle. The screech tone is higher with the baffles installed (as will be seen later in Fig. 10), and the higher excitation level is seen to drive the instability growth to a higher level nearer to the nozzle exit. When the baffles are moved downstream to interrupt the feedback loop and provide minimum screech level, the jet in Fig. 7 is seen to be very stable without any apparent flapping instability in the field of view. The shock cells are also clearly visible.

Quantitative data for the phenomena illustrated by the photographs in Figs. 5-7 will now be shown. The influence of screech level at the nozzle lip on the jet centerline total pressure for converging nozzle 4 operated underexpanded at a fully expanded Mach number (M_{exp}) of 1.55 is shown in Fig. 8. The reference condition, nozzle without baffles, is shown by the middle data set with a natural screech level at the nozzle lip of 156.2 dB and a potential core length of about 10 small nozzle dimensions ($X/H_{exit}=10$). When the screech blocking baffles are optimized, the screech level is seen to drop to

Fig. 5. Jet flapping mode due to screech excitation natural jet, nozzle 4, $M_{exp}=1.4$

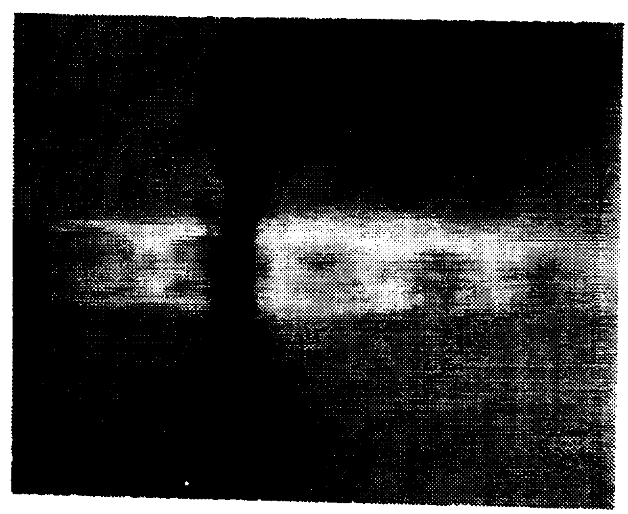


Fig. 7. Elimination of jet flapping mode with baffles located to minimize screech, nozzle 4, $M_{exp}=1.40$

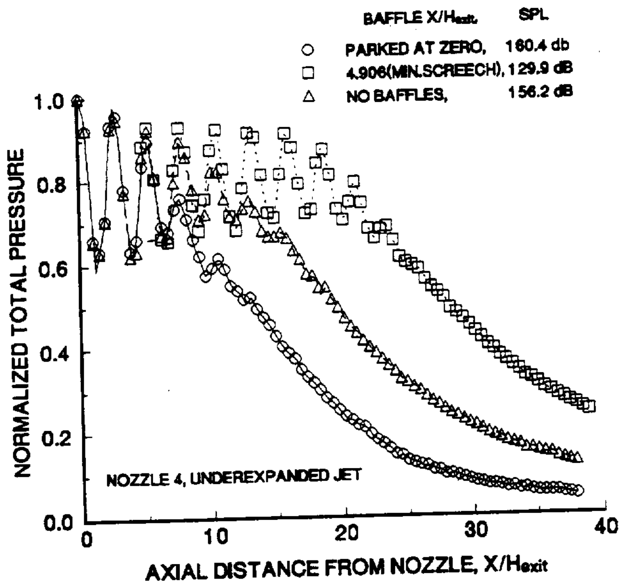


Fig. 8. Effect of screech level on supersonic jet mixing converging rectangular nozzle, M_{exp}=1.55

129.9 dB and the potential core length doubles to about X/H_{exit} = 20 (top data set). In addition when the baffles are parked at the nozzle exit, the screech level increases to 160.4 dB and the potential core length decreases to about X/H_{exit} = 5 (bottom data set Fig. 8). These results indicate a phenomenal change in jet mixing, a factor of four based on potential core length, due to a change in screech level of 30.5 dB. The screech tone is obviously exciting this very complex supersonic jet structure which has several shocks spaced axially along the jet. The high

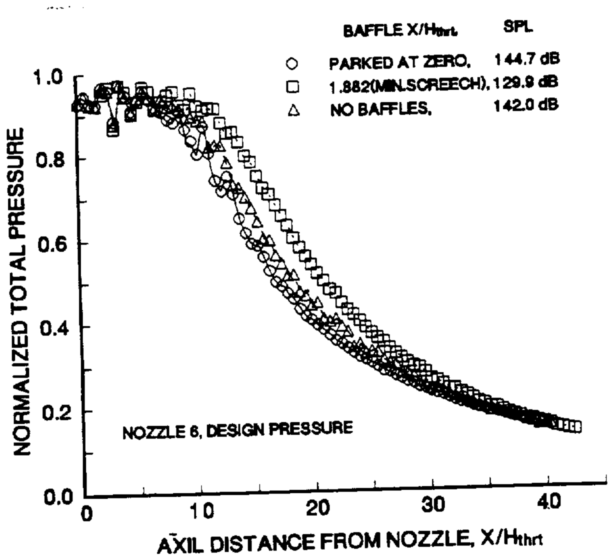


Fig. 9. Effect of screech level on supersonic jet mixing converging-diverging rectangular nozzle, M_{exp}=1.39

amplitude total pressure variations along the jet axis are due to these shocks. Note in Fig. 8 that nine shocks can be accounted for when the baffles are used to reduce screech and mixing. The results shown here are close to the maximum observed as Mach number was varied. An additional result at M_{exp}=1.4 will be shown shortly. These results seem to indicate that it may be dangerous to tamper with the screech level for an improperly expanded jet flow since the natural mixing for this jet may be seriously impaired.

The low screech level of a properly expanded jet flow for a converging-diverging nozzle may suggest that a poor mixing level might be expected because of the low level excitation at the nozzle lip. The influence of natural residual screech level for a properly expanded supersonic

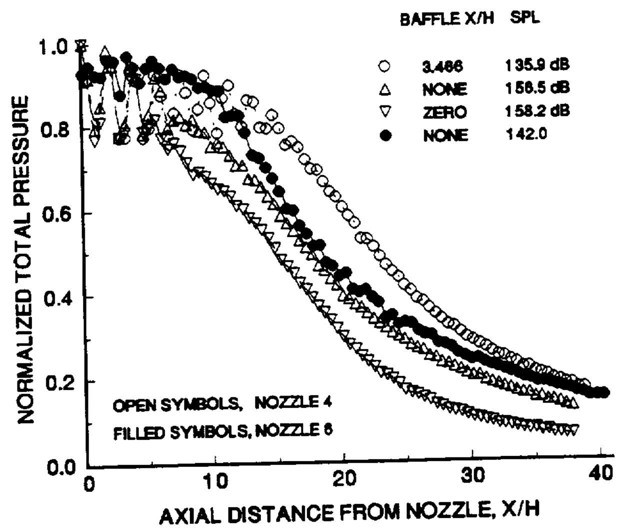


Fig. 10. Comparison of jet mixing from converging nozzle and converging-diverging nozzle at M_{exp}=1.4

jet from nozzle 6 is shown in Fig. 9. The screech levels are seen to be much lower than that of the underexpanded jet of Fig. 8 (142 vs. 156.2 dB) and alteration of screech with the baffles has a much smaller effect on jet mixing. Notice that the total pressure variations with axial position which are caused by the shock pattern in the flow are much smaller for the properly expanded jet. The fifteen decibel level between the curves in Fig. 9 does not seem to have a very large effect. This may seem puzzling at first but it should be noticed that all of the levels are quite low for the properly expanded jet. A comparison with an underexpanded jet (converging nozzle) at the same Mach number is shown in Fig. 10. The two jets show similar mixing in spite of the large difference in screech level (156.5 vs. 142 dB) for the unbaffled jets. This is a surprising yet extremely interesting result with profound practical considerations. It appears that the shear layers in these two jets have extremely different receptivities and/or instability growth rates. Recall that the shear layer of the underexpanded jet expands and contracts in the axial direction due to the several shocks while that of the properly expanded jet is essentially smooth. The structures in the jet which control mixing appear to be excited by much lower excitation levels. When the converging-diverging nozzle is operated underexpanded, the results are very similar to that of the converging nozzle. A much simpler more physical explanation for the above might also be relevant. The properly expanded jet from the C-D nozzle experiences a smooth expansion from the nozzle without large transverse pressure gradients. The instabilities can commence growth very near the exit. For the underexpanded jet, large symmetrical transverse pressure gradients dominate the flow as the flow first overexpands and then overcontracts as it forms the shock patterns downstream from the exit. This domination of the flow continues for many nozzle heights downstream until viscous effects break it up. However, the unsymmetrical pressure force of the screech feedback can superimpose upon this flow the flapping motion required to produce mixing of this jet.

Induced Screech and Jet Mixing

The jet mixing for the converging-diverging nozzle 6 discussed in the previous section was shown to be excited by low levels of excitation. High level natural screech excitation was not available since the shock structure in the flow which causes the screech was absent. In this section high levels of induced screech excitation will be produced by the paddles discussed in earlier sections. The paddles take the place of shocks in the feedback loop and it is because of this analogy that the "induced screech" terminology is used here.

Fig. 11. Stable jet from C-D nozzle 6 operated properly expanded, natural jet, $M_{exp}=1.396$

As in the previous experiment, the flow visualizations will be shown first. The Schlieren photograph of the jet produced from the converging-diverging nozzle 6 operating properly expanded at $M_{exp} = 1.396$ is shown in Fig. 11. Note that the flow looks very smooth with only very weak shocks and a gradual growth of a mixing layer. Some flapping instability was observed in the video sequence at the extreme of the field of view. In Fig. 12 the same jet is shown with maximum transverse insertion of the paddles located at $X/H_{thrt} = 8.2$. Recall that the paddles are seen in end view in Fig. 12, the vertical bars

Fig. 12. Violent jet flapping mode induced by baffles at maximum insertion, C-D nozzle 6, $M_{exp}=1.396$

being the support posts for the paddles. The jet is seen to respond violently to the presence of the paddles. Large amplitude flapping instability oscillations are seen to grow fairly close to the nozzle. The flapping jet alternately impacts the two paddles producing out-of-phase forces on the two paddles thus producing the out-of-phase acoustic field on the two sides of the jet which in turn drives the flapping instability closing the feedback loop. Additional mixing is also created by the intense unsteady vorticity produced downstream from the paddles as the unsteady flow impacts upon the paddles.

Fig. 13 shows the effect on jet mixing due to inserting the paddles into the jet shear layers. Each increment of paddle insertion causes a greater reduction in the jet centerline total pressure and thus an increase in the jet mixing. The induced screech level at the nozzle lip

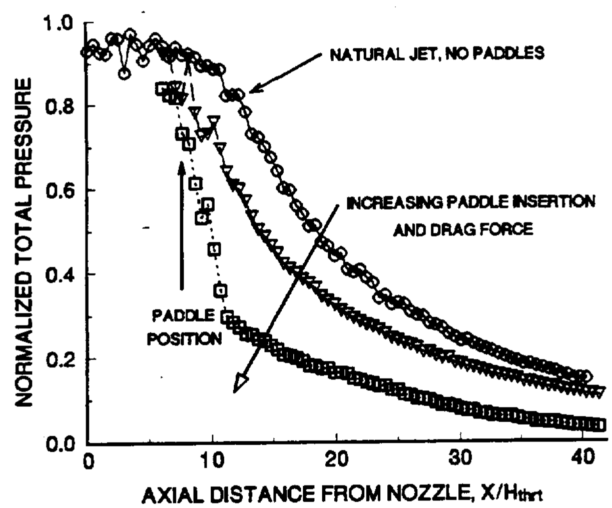


Fig. 13. Forced mixing of a supersonic rectangular jet using induced screech, C-D nozzle, design pressure, M_{exp}=1.39

increases from 142 to 157.8 dB for the range of insertion shown. Notice that the jet total pressure is dropping even upstream of the paddles. This is due to the violent flapping of the jet excited by the induced screech. The mixing enhancement is seen to be dramatic due to the paddles, but notice in Fig. 13 that attention is called also to an increase in drag due to the paddle insertion. At the maximum paddle insertion shown in Fig. 13, the total pressure measured on the paddle was 0.52 of the reservoir gage pressure and the drag on the two paddles was 0.21 of the jet thrust. The drag was reduced to 0.14 of the jet thrust by using paddles of half the length of the above. Mixing was also increased somewhat with these half-length paddles. These thrust losses are of course unacceptable but this should not detract from the proof of concept effort reported here with the use of the crude square cross-section paddles. Evidence already exits that the drag can probably be reduced by a factor of ten with only a small loss in jet mixing from the maximum shown in Fig. 13.

Three comparisons will now be made for the mixing with and without induced screech for the properly expanded jet from the converging-diverging nozzle. In

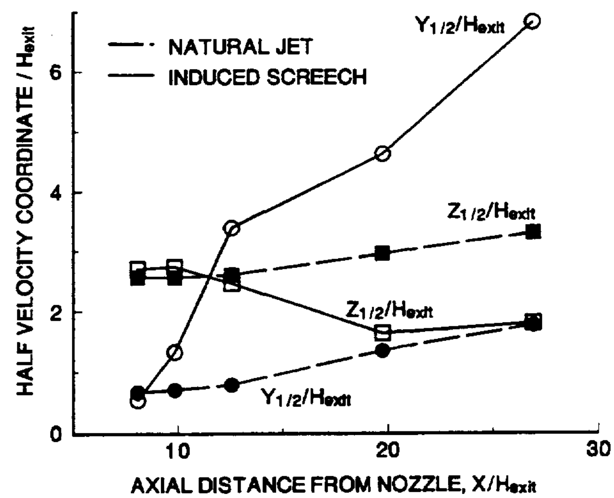
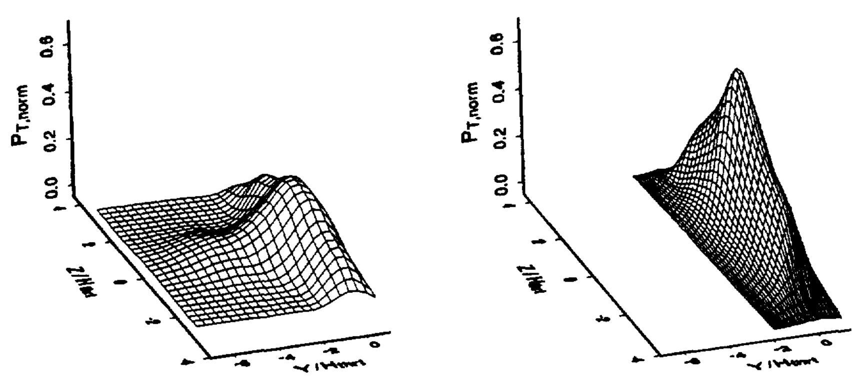


Fig. 15. Half velocity coordinates for excited jets, natural and induced screech, C-D nozzle 6, M_{exp}=1.39

Fig. 14 surface plots of the nozzle total pressure are shown with and without paddles with all scales being the same for both plots so direct comparisons can be made. The plots are obtained from a total pressure traverse over the transverse plane perpendicular to the nozzle axis at X/H_{thrt} = 14.2. With paddles the jet is seen to have a greatly reduced total pressure at the jet center and the flow is significantly spread out in the direction of the small nozzle coordinate (Y). This spread of the flow is due to the violent flapping of the jet in the Y direction. In Fig. 15 a facsimile of the familiar half-velocity coordinates for the two cases are shown as a function of axial distance from the nozzle lip. These are not really half velocity coordinates but instead one-quarter



a. Paddles at X/H_{thrt} = 8.1 b. No Paddles

Fig. 14. Jet mixing comparison with and without induced excitation C-D nozzle 6, M_{exp}=1.4, total pressure probe at X/H_{thrt}=14.2

total pressure coordinates which are sufficient for the discussion here. Notice that in the direction of the small nozzle coordinate ($Y_{1/2}$), the jet expands very rapidly due to the induced screech. This is of course just a quantitative expression of what is qualitatively seen in Fig. 14. In the large nozzle coordinate direction ($Z_{1/2}$) the jet is seen to diminish as measured by this quantity. It may be tempting to call the cross-over of coordinates as axis switching for the induced screech case. However, it is obvious here that this cross-over is just due to the drastic spread of the jet in the Y direction due to the violent flapping. Notice that no axis switching occurs for the natural jet either within the axial distance measured here. The total mass flow, combined jet and entrained, for the natural jet and the jet with induced screech are shown in Fig. 16. Notice that the entrained mass flow is substantially increased with the two curves diverging with increasing distance from the nozzle. The equivalent diameter, the circular jet diameter with equal area is used here for normalization since this is often used for comparisons of non-circular cross-sections. The increased mass flow here is an indication that the jet flapping is increasing the jet mixing in contrast to that of a flip-flop jet in an open environment as reported by Raman[5] et al. The difference between these two flapping jet cases is that of flapping instability wave length. In the present case the instability wave length is comparable to the jet dimension which results in true jet mixing. For the mentioned flip-flop jet the wave length is an order-of-magnitude larger than the jet dimension just giving an illusion of increased mixing.

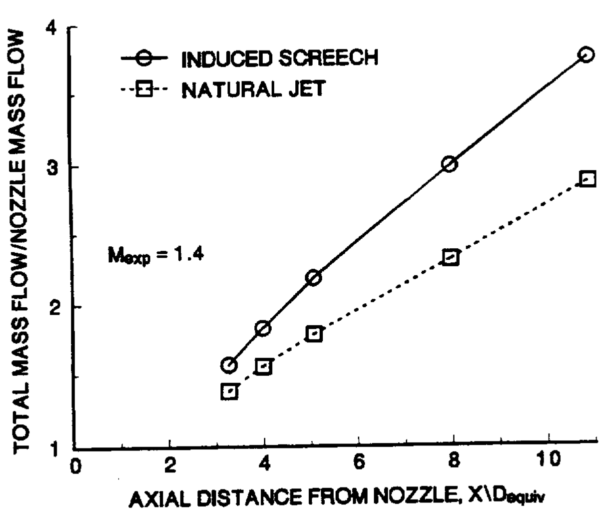


Fig. 16. Comparison of measured mass flow for jets, natural and induced screech, C-D nozzle 6, design pressure

Concluding Remarks

Some examples of experiments have been discussed regarding the effect of high amplitude excitation on the mixing of rectangular supersonic jets. The results have potential practical significance. The underexpanded rectangular supersonic jet has extreme mixing sensitivity to the level of natural screech at the nozzle lip. At a constant fully expanded Mach number of 1.55 for a converging nozzle, the potential core length of the jet could be altered by a factor of four by manipulation of the feedback loop with downstream baffles. It might be concluded that suppression of natural screech for such a nozzle configuration might result in an unwelcome reduction in jet mixing. This configuration, with its complex shear layer due to the axially distributed shocks, may also have a low receptivity and/or low instability growth rate which requires very large excitation amplitudes to accomplish good mixing in a short distance. On the contrary, the converging-diverging nozzle operated at design has jet mixing equal to the above naturally screeching nozzle although its residual screech level is very low due to the weak shock structure. It is thus tempting to also conjecture that this smooth fairly uniform shear layer has a high receptivity and/or instability growth rate which accounts for its fairly rapid mixing. The excitation level for this properly expanded supersonic jet can be greatly increased using induced screech generated by obstacles or paddles which take the place of the shock waves in the screech feedback loop. The jet responds with violently growing waves in the flapping mode which significantly increases the mixing rate of the jet as shown here by several different measures. The induced screech concept (similar to edge-tones) certainly has great practical potential. However, the drag losses incurred will have to be carefully defined to allow proper trade-off studies. Research will be conducted to determine paddle configurations with lower drag penalty than the crude first attempt rectangular shape used in this study.

Acknowledgement

The authors express their appreciation to William J. Ratvasky for the set up of the focused Schlieren system used in this research. Also appreciation is given to Brentley C. Nowlin, James E. Little, and Mary Ann J. Lupica for the design and fabrication of the strobe electronics for the Schlieren system. Appreciation is also expressed to Richard A. Brokopp for his devotion in bringing the test cell to its excellent operating condition and to Ralph Fallert for putting it all together. Thanks to you all.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1993	Technical Memorandum

4. TITLE AND SUBTITLE

Enhanced Mixing of a Rectangular Supersonic Jet by Natural and Induced Screech

5. FUNDING NUMBERS

WU-505-62-52

6. AUTHOR(S)

Edward J. Rice and Ganesh Raman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-7964

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-106245
AIAA-93-3263

11. SUPPLEMENTARY NOTES

Prepared for the AIAA Shear Flow conference sponsored by the American Institute of Aeronautics and Astronautics, Orlando, Florida, July 6-9, 1993. Edward J. Rice, NASA Lewis Research Center, Cleveland, Ohio, and Ganesh Raman, Sverdrup Technology, Inc., Lewis Research Center Group, Brook Park, Ohio 44142. Responsible person, Edward J. Rice, (216) 835-2594.

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Unclassified - Unlimited Subject Category 02	

13. ABSTRACT ***(Maximum 200 words)***

The influence of shear layer excitation on the mixing of supersonic rectangular jets was studied experimentally. Two methods of excitation were used to control the jet mixing. The first used the natural screech of an underexpanded supersonic jet from a converging nozzle. The level of the screech excitation was controlled by the use of a pair of baffles located to block the acoustic feedback path between the downstream shock structure and the nozzle lip. A screech level variation of over 30 decibels was achieved and the mixing was completely determined by the level of screech attained at the nozzle lip. The second form of self-excitation used the induced screech caused by obstacles or paddles located in the shear layers on either long side of the rectangular jet. With sufficient immersion of the paddles intense jet mixing occurred and large flapping wave motion was observed using a stobed focused Schlieren system. Each paddle was instrumented with a total pressure tap and strain gages to determine the pressure and drag force on the square cross-section paddle. Considerable drag was observed in this initial exploratory study. Future studies using alternate paddle geometries will be conducted to maximize jet mixing with minimum drag.

14. SUBJECT TERMS

Jet mixing; Enhanced mixing; Screech; Induced screech; Edge-tones; Rectangular jet; Supersonic jet

15. NUMBER OF PAGES

14

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102